Forecasting Research

Forecasting Research Division
Technical Report No. 137

Experiments with Scaling the Soil Moisture Climatology

by

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January 1995

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1. INTRODUCTION

The soil moisture is an important controlling factor in the evapotranspiration[1] from the surface which, at least in part, modulates the partitioning of the total energy flux between latent and sensible heat fluxes. When soil moisture is high then evapotranspiration is high, given that the atmosphere is able to absorb the moisture, and therefore the latent heat flux is increased. Conversely, when soil moisture is low then evapotranspiration is restricted but the ground surface warms up more so increasing the sensible heat flux.

These fluxes are important in determining the near surface temperature which in turn may affect other atmospheric parameters. Over land, the evapotranspiration may be the only source of moisture which may influence cloud cover and precipitation. Dirmeyer and Shukla (1993) showed that as a global mean, 60% of continental precipitation is due to evaporation from the soil. A fuller discussion of the affects of soil moisture content is given by Jones (1994).

This paper describes some of the problems with soil moisture that are in the operational model and experiments with a new soil moisture climatology which is designed to be more consistent with the model physics to aid a greater understanding of the problems.

During October 1994 a change made to the assimilation system was tested by Bell (1994) and a brief description of the impact of this change on the soil moisture is also given.

2. Soil Moisture in the Operational Global Model.

The soil moisture content is a prognostic variable in the operational global model. The starting soil moisture in any given analysis is the short term forecast from the previous forecast run of the model. The evolution of the soil moisture content is thus highly dependent upon the assimilation cycle of the model.

The soil moisture in the model is reset weekly to a climatological value. The climatology used is that created by Willmott et al (1985) with modifications described in Jones

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[1]The term evapotranspiration is preferred as it includes both evaporation from the soil surface and transpiration from plant stomata which in turn is partly controlled by the soil moisture content and the plant physiology

(1993). Figures 1 and 2 show the change in soil moisture from the initial climatological value over a week in November. This particular week is from the climatological values set on the 11 November to the 00Z analysis on the 17 November but is typical of the weekly change that is observed during the Southern Hemisphere winter.

It can be clearly seen that there is a general drying in the equatorial and tropical regions, more clearly seen in the regional plots. The drying is generally around 30 kgm^{-2}. There are however, some areas with a significant gain in the soil moisture, notably in South America, orientated SW to NE between the two areas of drying, Africa, just south of the drying zone and the Indonesian islands. In these areas the increase in soil moisture is as much as 250kgm^{-2}, although values this high are isolated grid points.

The patterns of drying and wetting may be the result of genuine weather conditions but since the patterns are similar for a period of weeks, this seems unlikely. The pattern in Africa may be the result of a genuine climatological anomaly in the location of the ITCZ. Such an anomaly would last for several weeks so it is difficult to draw any conclusions of whether this pattern is genuine or a problem in the model without looking at different years.

Figures 3 and 4 show the change in soil moisture content from 00Z 2 June 1994 to 0Z 8 June 1994, ie Northern Hemisphere summer. Now there are still zones of drying in the tropical and equatorial regions but the main area of drying has shifted to the continental land masses of North America and Eurasia. Again, this pattern is typical to what occurs during the northern hemisphere summer.

The drying problem appears to be related to the season, most pronounced in areas where it is summer. I shall now suggest why this should be the case.

Moisture is lost from the soil through both evapotranspiration and sub-surface runoff through gravitational drainage. The only method by which moisture can be added is by precipitation, either immediate in the case of rainfall, or delayed as in the case of snow melt. Lorenc (1992) has shown that there is a spin-up problem of relative humidity in the assimilation. This leads to inadequate rainfall but the evapotranspiration continues regardless of this and so the soil moisture content decreases. Evapotranspiration increases during the summer months hence the patterns that are seen, although it is somewhat puzzling that the patterns observed in the equatorial regions are not more similar in November and June.

It is for this reason that the soil moisture content in the model is reset to the climatology value each week. (This has since been changed to each day). This however, is not desirable as the climatological dataset uses a different soil moisture model to the one used in the Unified Model (UM) and this has lead to some conflict and some of the modifications made are designed to alleviate these. Secondly, genuine climatological anomalies in the soil moisture content field will not be identified and this may give rise to forecasting errors.

Willmott et al used a maximum value of soil moisture of 150kgm^{-2} whereas the maximum soil moisture content allowed in the UM at any one grid point depends upon the soil and vegetation characteristics at that grid point and this leads to a range of values from 0kgm^{-2} to values above 400kgm^{-2}. In some areas the climatological soil moisture values are too high for the vegetation and soil leading to too high latent heat fluxes. This is apparent in the Sahel region of Africa, at about 15°N, (Rowntree - personal communication). Indeed, some of the apparent drying may be a result of the model trying to equilibrate the soil moisture with the prescribed vegetation and soil conditions. Therefore, the first stage in trying to understand the problems is to use a climatological soil moisture dataset that is consistent with the physics of the UM. This is what is attempted here.

3. SCALING THE SOIL MOISTURE CLIMATOLOGY

All previous modifications applied to the Willmott et al data were removed and then the following scaling was applied.

$$m' = Fm$$

where,

$$F=((\chi_f-\chi_w)D_R\rho_w)/150$$

m' - new soil moisture values (kgm^{-2})
m - original soil moisture value (kgm^{-2})
χ_f - volumetric soil moisture concentration at field capacity
χ_w - volumetric soil moisture concentration at wilting point
D_R - root depth (m)
ρ_w - density of water (1000kgm^{-3})

The soil and vegetation characteristics are as defined by Wilson and Henderson-Sellers (1985) and created as described in Jones (1993) .

The value of F is plotted in figure 5, Over much of the

globe F is less than 1.0, ie soil moisture is reduced in these areas. It is only in the equatorial rain forest areas where the soil moisture is actually being increased, by over double in some places. The global average of F is 0.675883 with a standard deviation of 0.473545.

The snow amount climatological field was also altered slightly so that all land ice points as defined by WHS are given a snow amount value of 50000 $kgm^{-2}s^{-1}$. This has changed some points in southern Alaska and also some coastal points over Greenland which currently have a snow amount value of 50000 $kgm^{-2}s^{-1}$ now have a value much reduced as WHS do not define those points as land ice.

4. EXPERIMENTS AND RESULTS

To test the performance of the new soil moisture dataset two experiments were performed. The control experiment was a 6 day forecast from the analysis at 00Z 10 Nov 1994 configuring the current soil moisture climatology. The test experiment was a 6 day forecast from the same analysis but configuring the new soil moisture climatology. Neither experiment included assimilation of observations.

Figures 6 and 7 show the starting soil moisture conditions in the control and test experiments respectively. It can be seen that there is an increase in the initial soil moisture in the equatorial regions, as would be expected from the map of F in figure 5. It can also be seen that soil moisture has been reduced over much of the Northern hemisphere north of 45N. Part of this is the value being less than 1.0 in this region and partly due to the removal of the previous minimum value of $50kgm^2$.

Figures 8 and 9 show the difference between the two starting conditions. These show that the soil moisture has been increased by over 100 kgm^{-2} in parts of the equatorial rain forest regions.

Figures 10 and 11 show the T+144 forecast of soil moisture in the control and test runs respectively. In both experiments the general shape of the soil moisture field has remained the same. There has been an increase in soil moisture in the equatorial regions. Figures 12 and 13 show the difference between the soil moisture in the control and test experiments at T+144. It is difficult to find many differences to figures 8 and 9. This means that the relative difference between the two experiments has remained reasonably constant. This is further seen in figures 14,15, 16 and 17 which show the change in soil moisture within the two runs.

Thus we can conclude that the evolution of the soil moisture is independent of the initial conditions. Although it has to be assumed that those initial conditions are feasible even if not correct.

Figures 18 and 19 show the zonal means of the soil moisture through the control and test forecasts. These show clearly that in the test run there is less soil moisture in northern high latitudes and more in the equatorial region, confirming what is seen in the earlier maps. What is also seen is that in both runs moisture is being gained in the equatorial regions but there is more soil moisture being added in the control run. This suggests that the initial soil moisture in the test run is more realistic, or at least more consistent with the vegetation and soil in these areas.

It is also noticeable that the drying zone in South America is apparent in the two forecasts although by a reduced amount than change in the analyses. The relative change in the two runs is about the same suggesting that there is insufficient rainfall in the forecast.

5. EFFECT ON OTHER ATMOSPHERIC PARAMETERS

A number of other atmospheric parameters, both instantaneous and accumulations were examined for any noticeable impact. A general description of the observed affects, with figures where appropriate, is given below. The results will be discussed later.

ACCUMULATIONS

Surface and Boundary Layer Total Moisture Flux ($kgm^{-2}s^{-1}$)

The total accumulation of this flux over a 6 day forecast is only in the order of 0.1 $kgm^{-2}s^{-1}$ so any small change will result in a large percentage change. This is seen in two areas, the Western Sahel and Australia, shown in figure 20. The magnitude of these flux has been reduced by 100% in some areas. A modest increase, of about 5%, was seen in South America (not plotted).

Evaporation from soil surface

The only area with a significant change is Western Australia where this accumulation has been decreased by up to 16 $kgm^{-2}s^{-1}$ in places, a percentage reduction of almost 100%. See figure 21.

Evaporation from canopy (Not plotted)

Some extensive but only very small differences in the two runs. The magnitude of the differences were generally less than 1 $kgm^{-2}s^{-1}$ representing a percentage change of less than 1%.

Large Scale rainfall (Not plotted)

Some extensive but generally very small differences less than 0.1 $kgm^{-2}s^{-1}$. There were also a few areas which experienced an increase in rainfall of upto 6 $kgm^{-2}s^{-1}$, notably in the Tasman Sea.

Large Scale snow amount (Not plotted)

Some extensive but very small differences, less than 0.1 $kgm^{-2}s^{-1}$.

Convective rainfall (Not plotted)

Again extensive but general very small differences although the extreme differences are about 25 $kgm^{-2}s^{-1}$ but these are isolated grid points.

Convective snow amount (Not plotted)

Again some extensive but extremely small differences.

Several other accumulations were examined and none gave any significant differences, although the sub surface runoff did increase by about 50 $kgm^{-2}s^{-1}$ over Indonesia.

INSTANTANEOUS FIELDS

Fields of low, medium and high cloud, geopotential height at 500mb and 850mb and surface temperature were examined at every 24 hours during the forecast. The only field to show some significant changes was the surface temperature field. The global difference at T+24 and T+144 is shown in figures 22a-b. At T+24 there are a few areas where a the test experiment is slightly cooler but generally less than 1K. The most extensive area is South America where the soil moisture has been dramatically increased which leads to a reduction in surface temperature as explained earlier. The same argument can be used to explain most of the other areas which show a slight decrease in surface temperature, although since the differences are so small it is difficult to be certain as their exact cause. The differences become more extensive by T+144, as would be expected, a slight change early in the forecast amplifies through the forecast.

One interesting difference is over Western Australia,

shown in figures 22. Here at T+24 there is a very significant increase in surface temperature at around 5K. The difference is all but gone at T=144.

The reason for the difference is that the control run has soil moisture of about 15 $kgm^{-2}s^{-1}$ in this area which has been reduced to 0 $kgm^{-2}s^{-1}$ in the test run. This is only a modest decrease but the extreme temperatures in this area, around 40 °C, exaggerate the effect. By T+144 the soil moisture has been dried out of the control run so the temperature forecast in the two runs agree. It seems reasonable to assume that there shouldn't be any soil moisture in this area, the area being desert, and that the test run is more realistic.

Unfortunately, it is difficult to verify land surface temperatures against observational data as this parameter is not generally observed. It cannot be compared to screen temperatures as screen temperatures are measurements of the air temperature at a height of a couple of meters above the ground surface.

7. PARALLEL SUITE TRIALS

In October 1994 a change to the assimilation cycle proposed by Bell (1994) was tested by a parallel suite trial. As part of the trial the soil moisture was not reset to climatology. The climatology used in these trials is the original climatology, not the new scaled climatology.

Figure 24 shows the difference between the soil moisture in the operational model and the parallel suite trial on the 20 October 1994. This is effectively the departure of the soil moisture from climatology during a period of 6 days.

Similar patterns to those found in the previous experiments are clearly seen with drying over South America, India and Australia. The zonal pattern in Central Africa is once again seen and there is also a significant wetting in Texas, due to the remnants of Hurricane Rosa.

The operational field (ie climatology) has a global mean of 38.7271194kgm^{-2} and the parallel analysis has a global mean of 38.2661362kgm^{-2}. The mean of the field shown in figure 24 is 0.460981756kgm^{-2}. This confirms that there is still a drying trend of the soil moisture in the assimilation cycle of the model.

To confirm that the drying trend is due to the assimilation cycle and not the model in general, the global mean of the forecast soil moisture fields were calculated. The figures are shown in the table below.

	VERIFICATION TIME						
	14/10	15/10	16/10	17/10	18/10	19/10	20/10
T+0	38.363	38.368	38.237	38.198	38.154	38.311	38.267
T+24		38.516	38.235	38.163	38.259	38.213	38.177
T+48			38.684	38.269	38.265	38.471	38.286
T+72				38.966	38.677	38.600	38.680

Table showing the global mean soil moisture content (kgm^{-2}) in the parallel suite trial. The figures are given for the time the fields are valid.

The mean of the soil moisture at T+0 is always less than the T+48 and T+72 forecasts valid for the same time. There is rather more fluctuation at T+0 and T+24, the times dominated by the assimilation cycle.

Once the forecast goes beyond T+24 there is a clear signal of wetting. Before then the signal is rather confused with 4 occassions of drying between analyses and 2 of wetting. However, the changes are very small indicating.m

The global changes may be small but as has been decribed in this paper there are very large regional changes. There is a suggestion that the drying problem is confined to the assimiation cycle and early part of the forecast, indicating a spin-up problem, but a much longer trial is required to draw any firm conclusions. Thus, a longer assimilation is planned.

6. CONCLUSIONS

This paper has described a test using the Willmott et al soil moisture climatology scaled to be consistent with the vegetation and soil model used within the UM. It was motivated by the fact that there appears to be a problem of the soil moisture drying in certain regions in the operational global model. The parallel suite trials in November 1994 show that the problem lies within the assimilation cycle of the model rather than within the forecast model itself.

The experiment did show that the evolution of the soil moisture in the forecast is independent of the initial soil moisture in most parts of the world.

As was stated in section 2 there is also a problem with some areas having too high soil moisture, such as the Sahel along 15N. The scaled soil moisture did reduce the latent heat flux in this area.

Impact on other atmospheric parameters was generally negligible. This is perhaps not surprising as the soil moisture is only one part of a very complex system. The one area of significant differences, Western Australia, is difficult to verify due to the lack of observational data of this parameter.

The experiments and the parallel suite trial do show that 6 days is too little time in which to properly assess the behaviour of the soil moisture field. he parallel suite trial also confirms that the problem is within the assimilation cycle rather than the forecast model.

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Wilson, M.F. and Henderson-Sellers, A. (1985). 'A global archive of land cover and soils data for use in general circulation climate models'. *Journal of Climatology*, **5**, pp119-143.

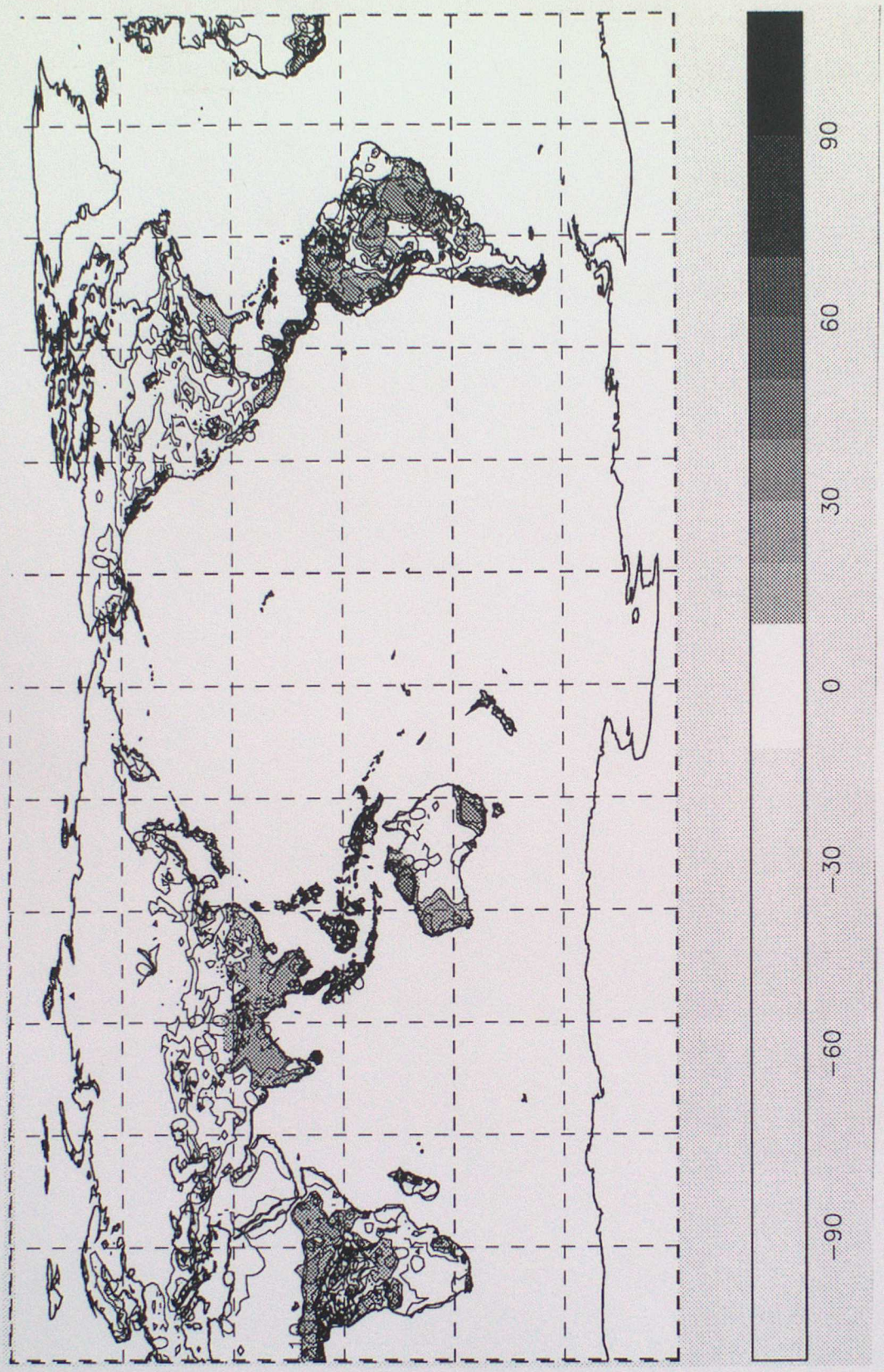

Figure 1: Change in soil moisture content (kgm^{-2}) in operational model from being reset to climatology at 12Z on the 11 Nov 1993 and 00Z on 17 Nov 1993. Contours drawn every $10kgm^{-2}$, greyscale shading used for positive values, ie areas which have shown a decrease in soil moisture content.

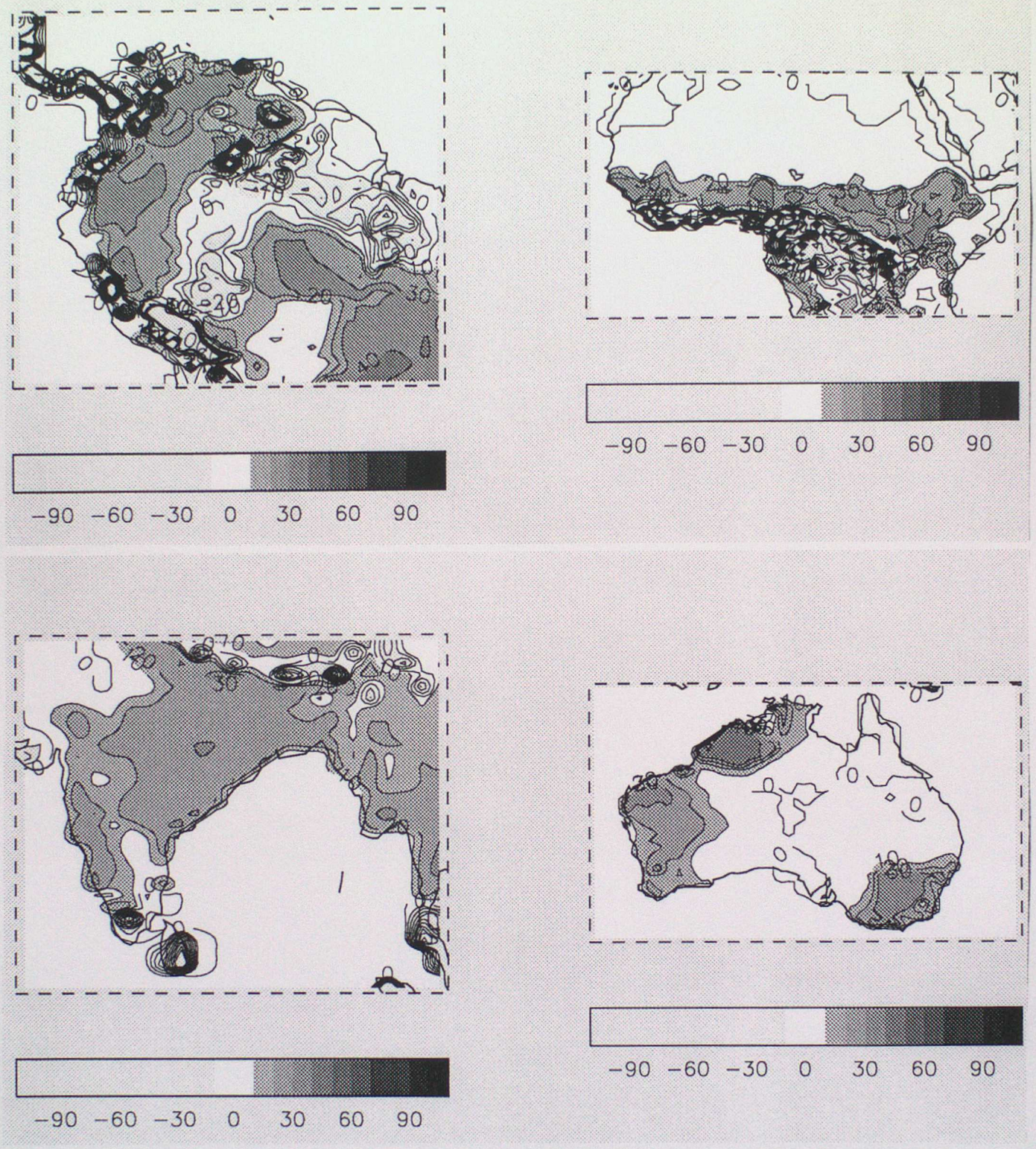

Figure 2: Change in soil moisture content (kgm^{-2}) in operational model from being reset to climatology at 12Z on the 11 Nov 1993 and 00Z on 17 Nov 1993. Contours drawn every $10kgm^{-2}$, greyscale shading used for positive values, ie areas which have shown a decrease in soil moisture content.

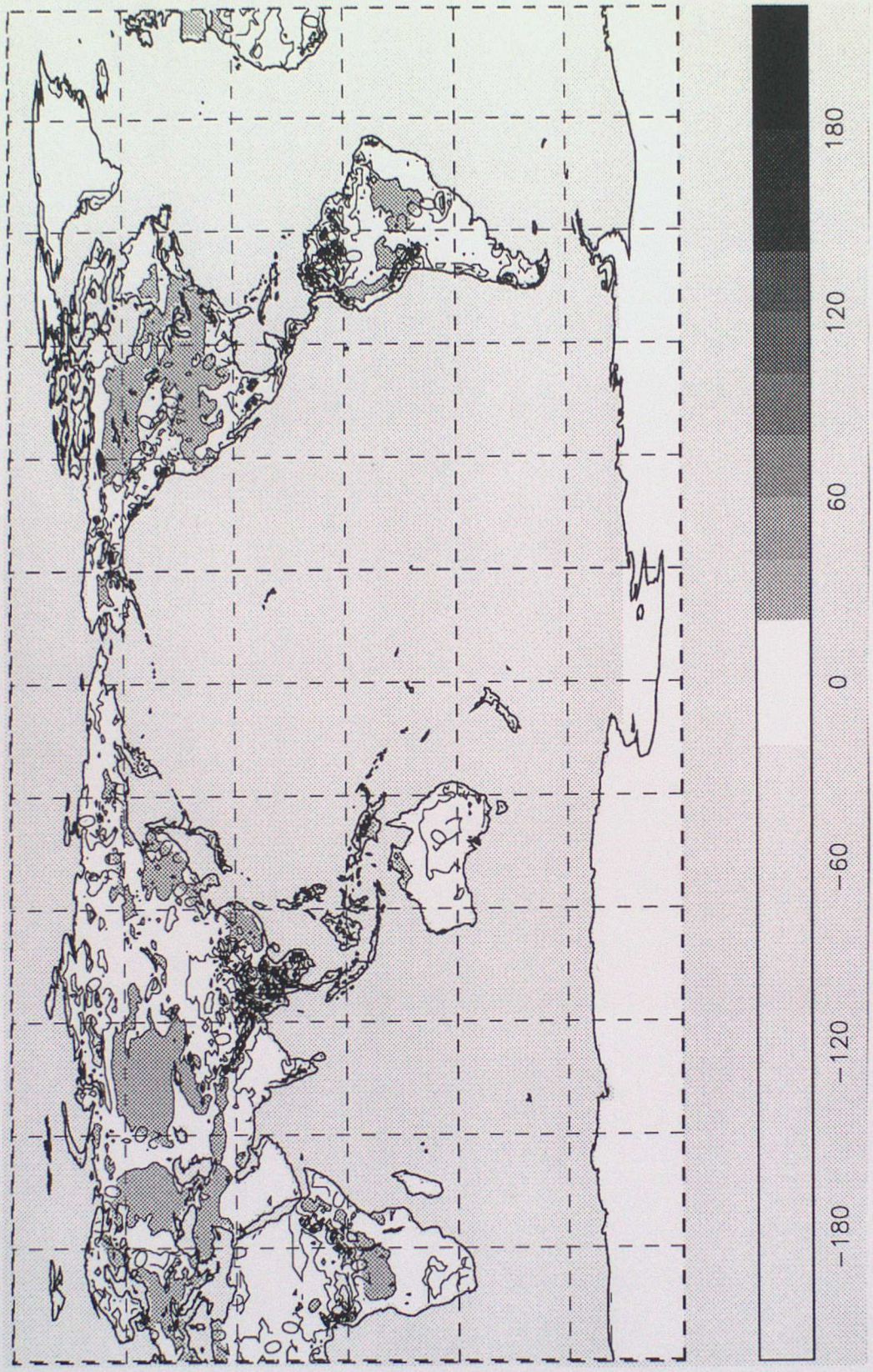

Figure 3: Change in soil moisture content (kgm^{-2}) in operational model from being reset to climatology at 12Z on the 02 Jun 1994 and 00Z on 08 Jun 1994. Contours drawn every $10kgm^{-2}$, greyscale shading used for positive values, ie areas which have shown a decrease in soil moisture content.

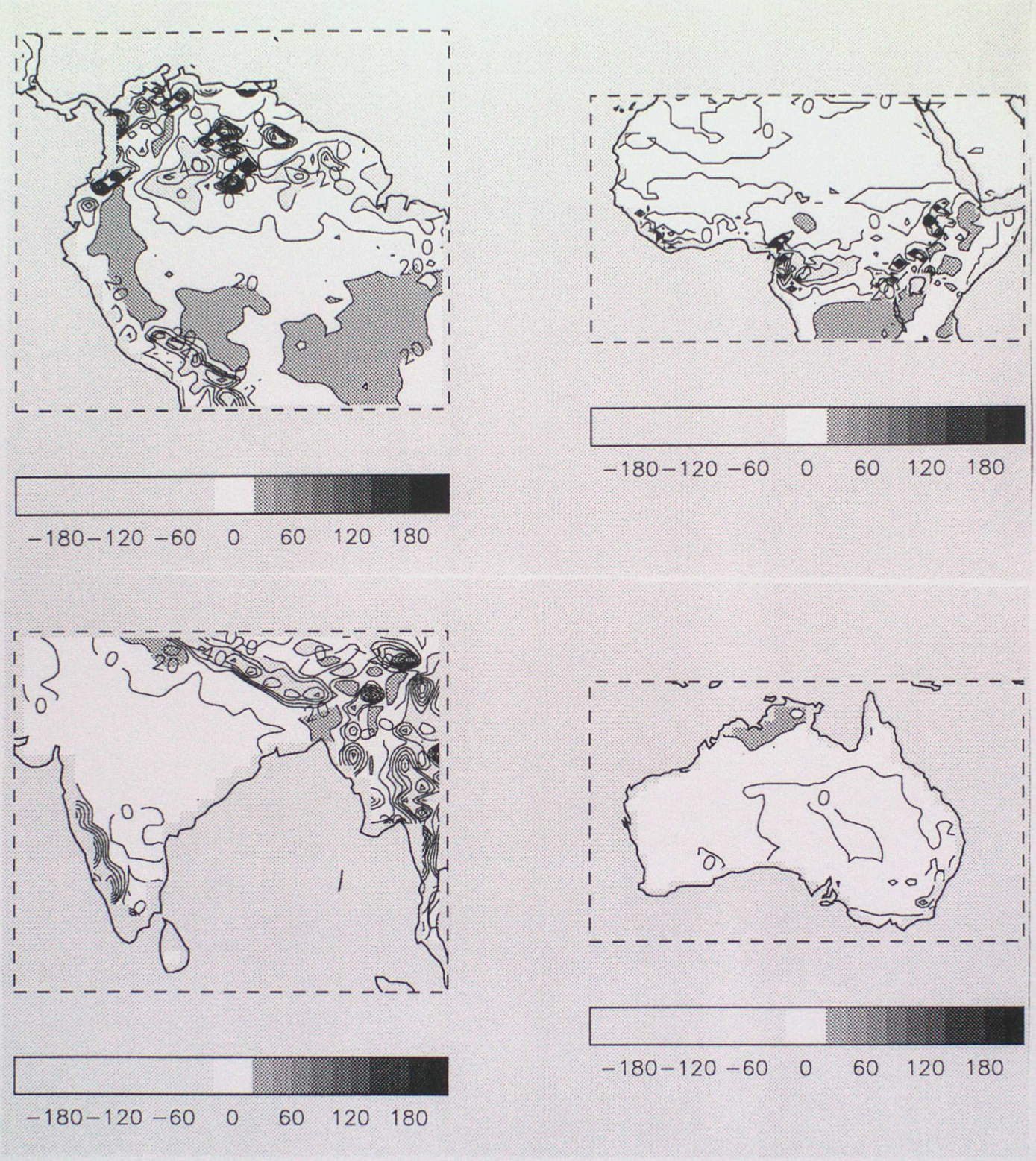

Figure 4: Change in soil moisture content (kgm^{-2}) in operational model from being reset to climatology at 12Z on the 02 Jun 1994 and 00Z on 08 Jun 1994. Contours drawn every $10kgm^{-2}$, greyscale shading used for positive values, ie areas which have shown a decrease in soil moisture content.

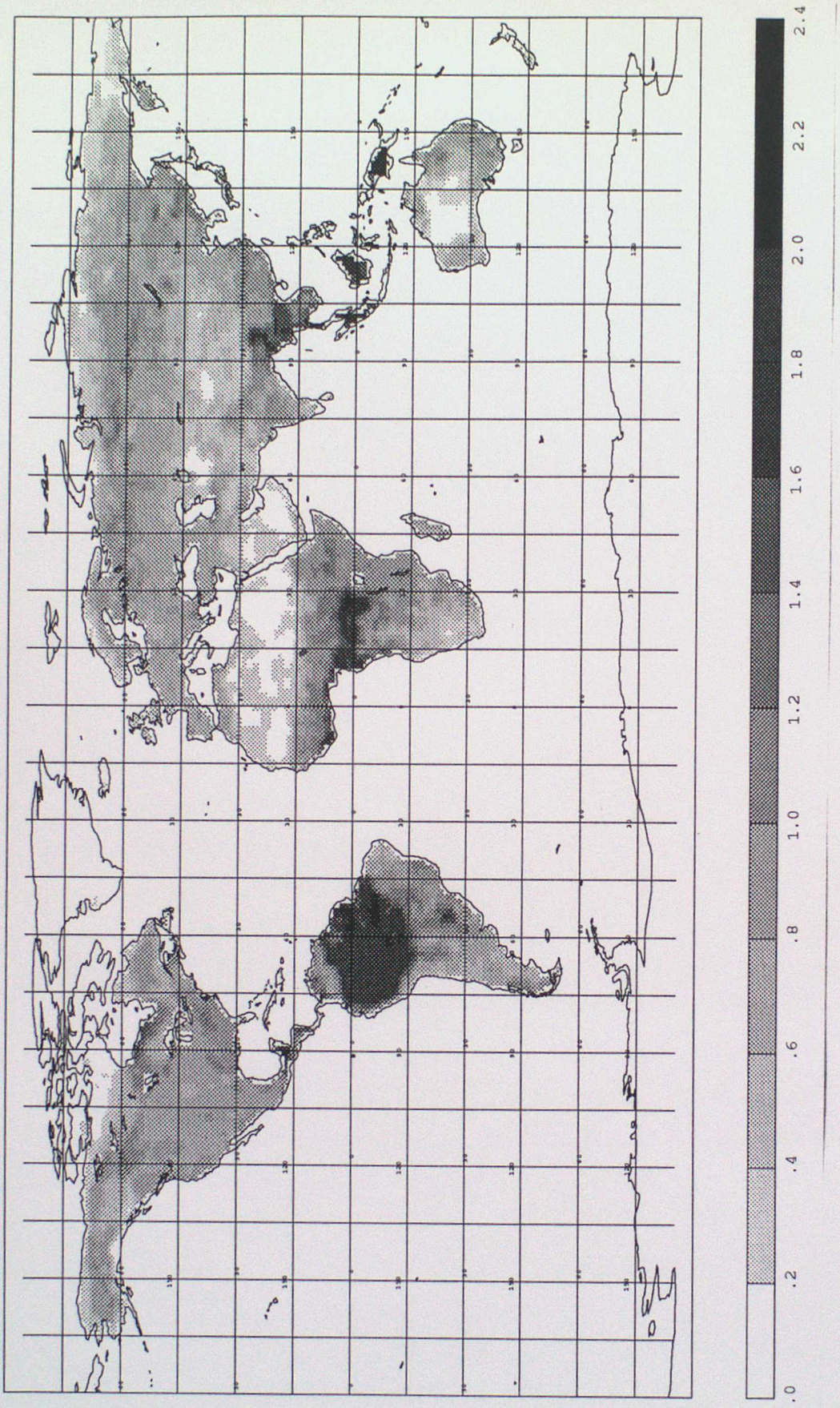

Figure 5: Scaling factor (F) applied to basic soil moisture climatology. Contours and gre scaling every 0.2.

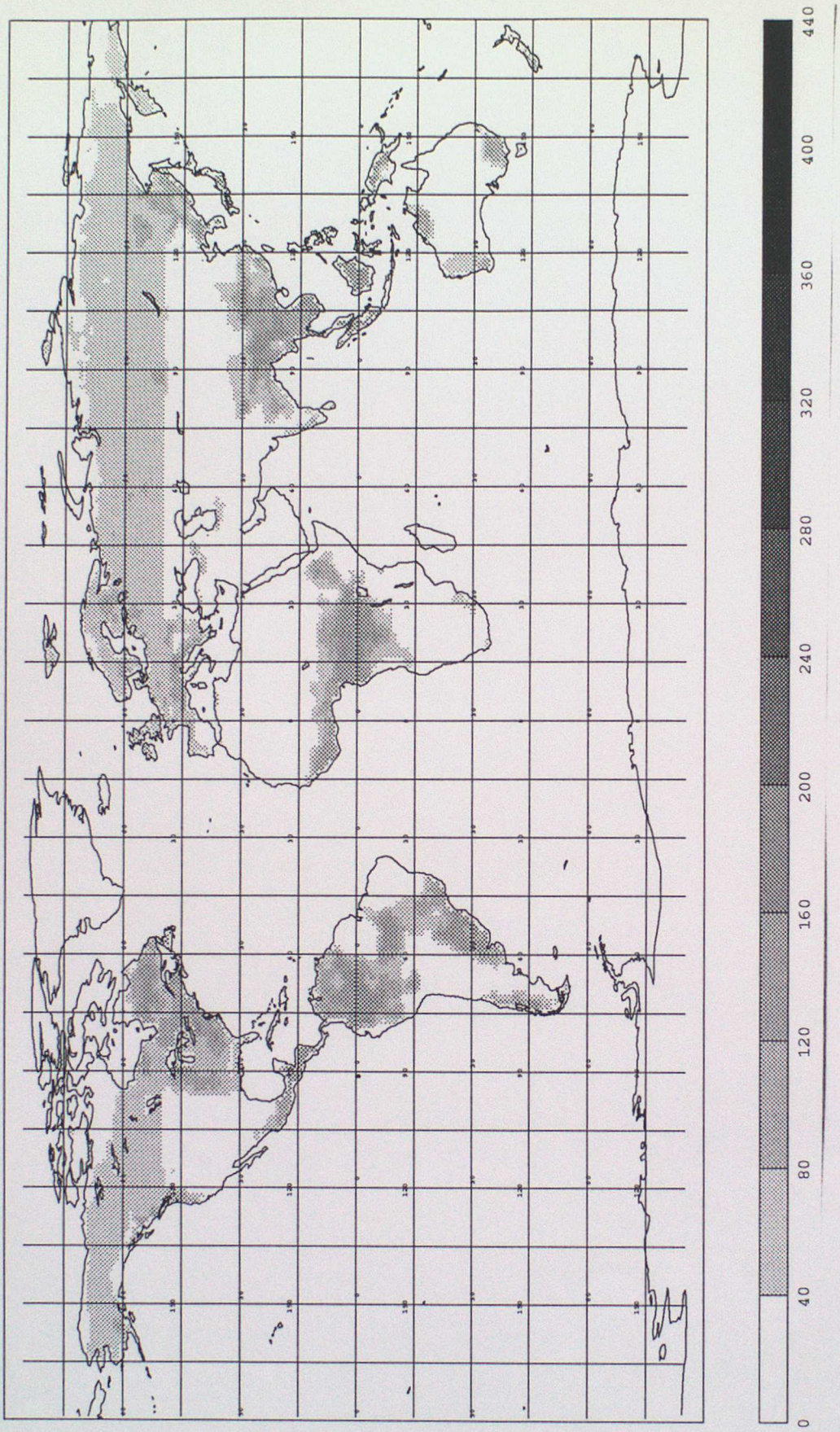

Figure 6: Soil moisture content at start of control experiment. Values shaded every 40kgm^{-2}.

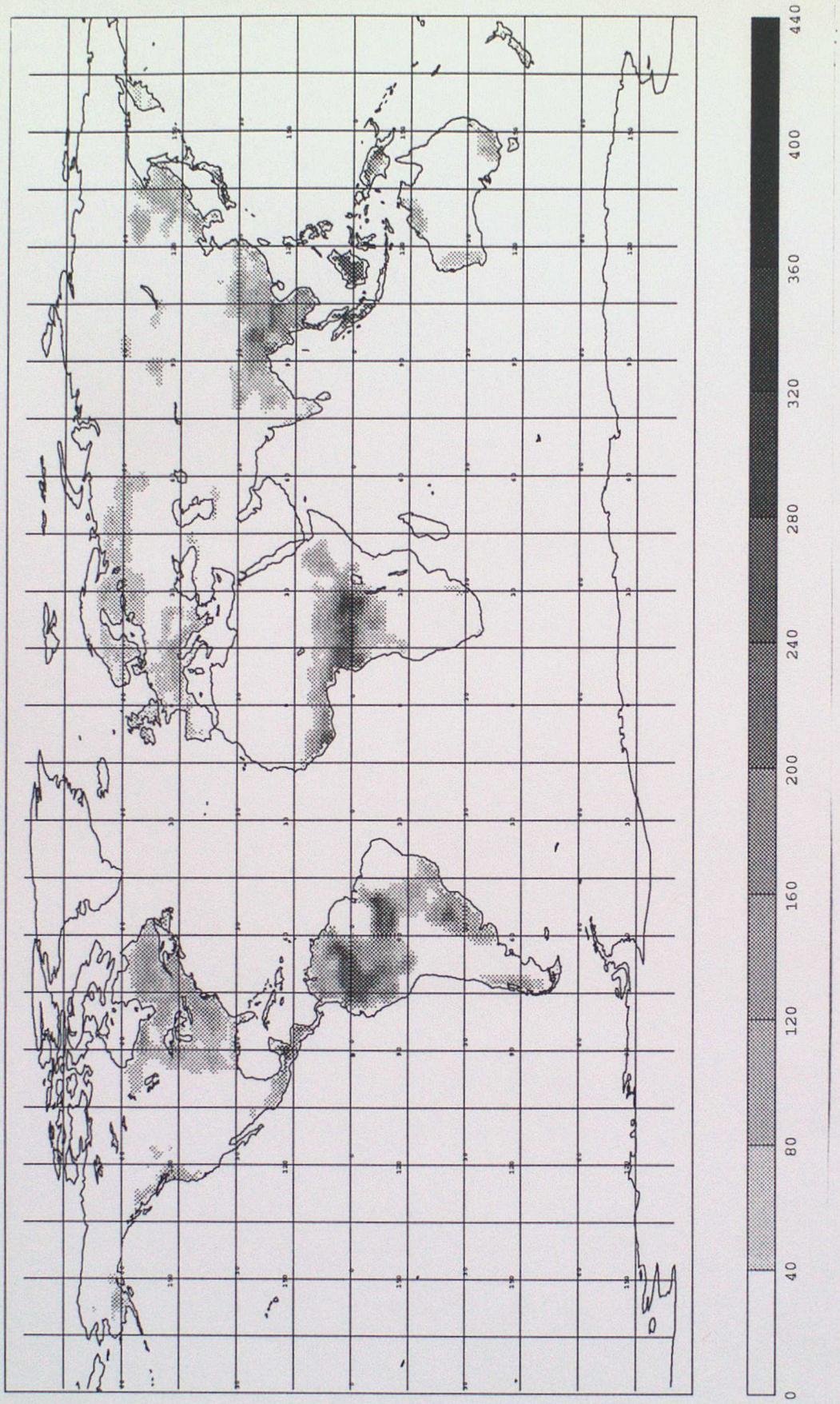

Figure 7: Soil moisture content at start of test experiment. Values shaded every 40kgm^{-2}.

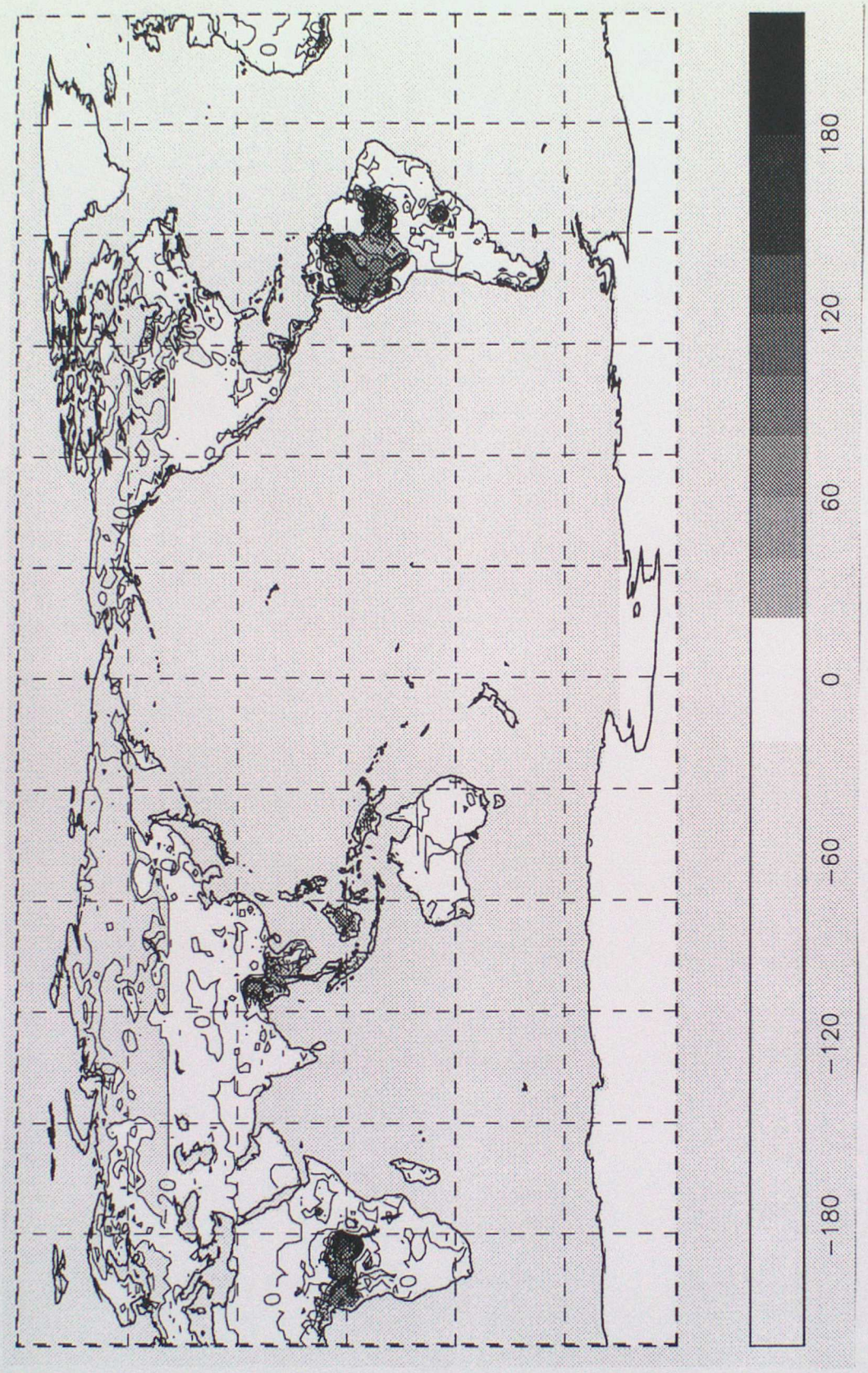

Figure 8: Soil moisture at start of test experiment minus soil moisture at start of control experiment. Contours drawn every 20kgm^{-2}.

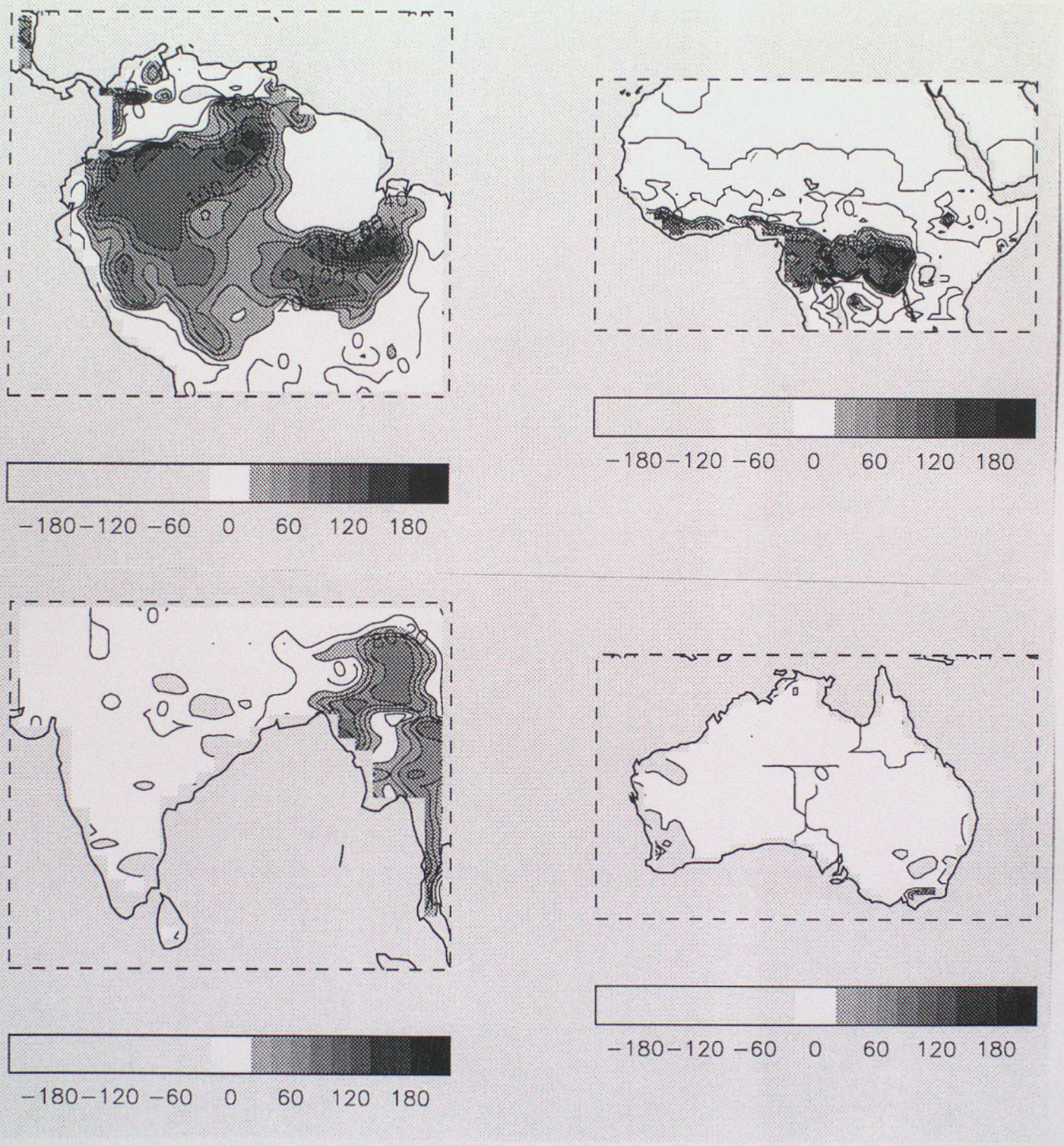

Figure 9: Soil moisture at start of test experiment minus soil moisture at start of control experiment. Contours drawn every 20kgm^{-2}.

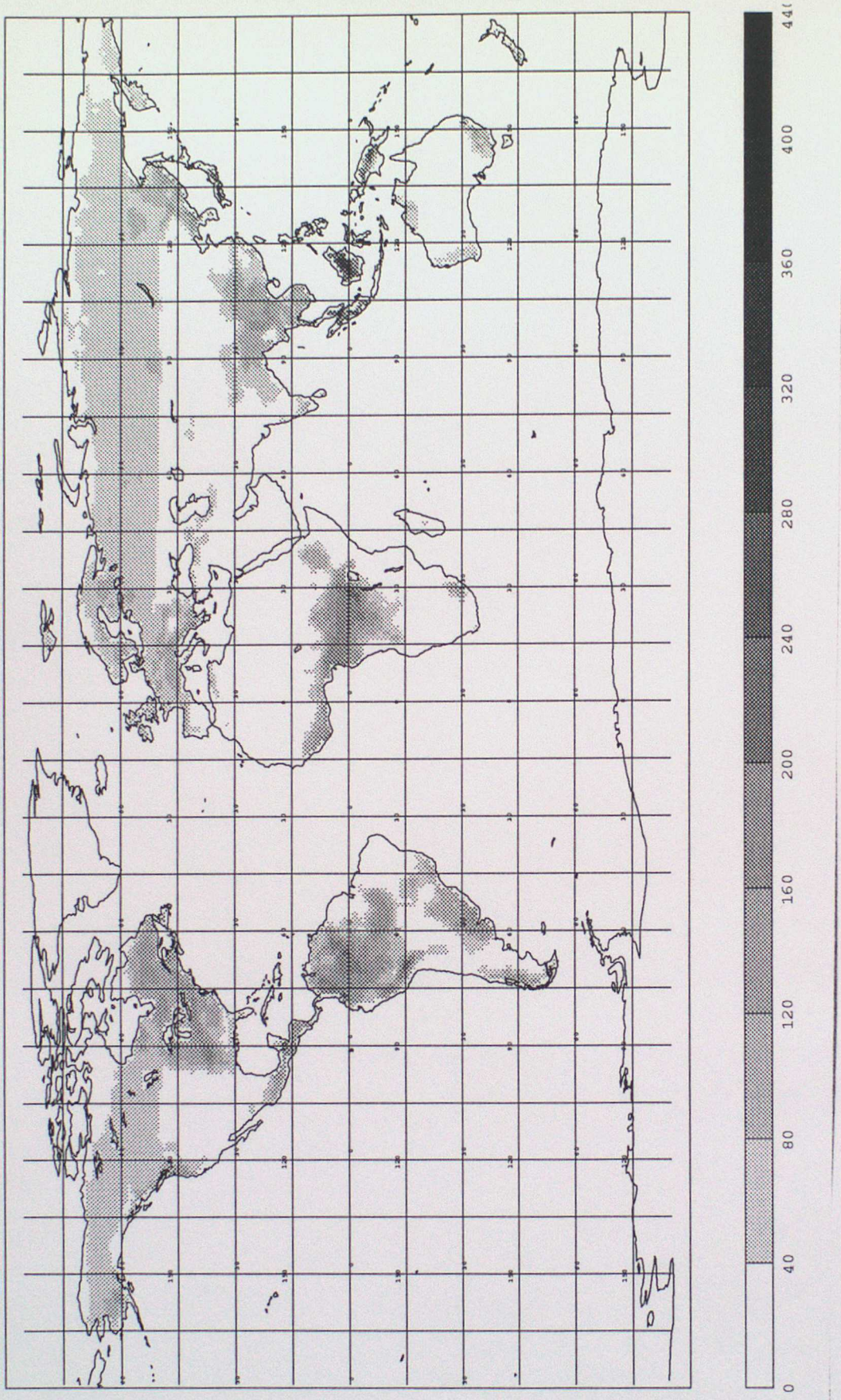

Figure 10: Soil moisture content at end of control experiment. Values shaded every 40kgm^{-2}.

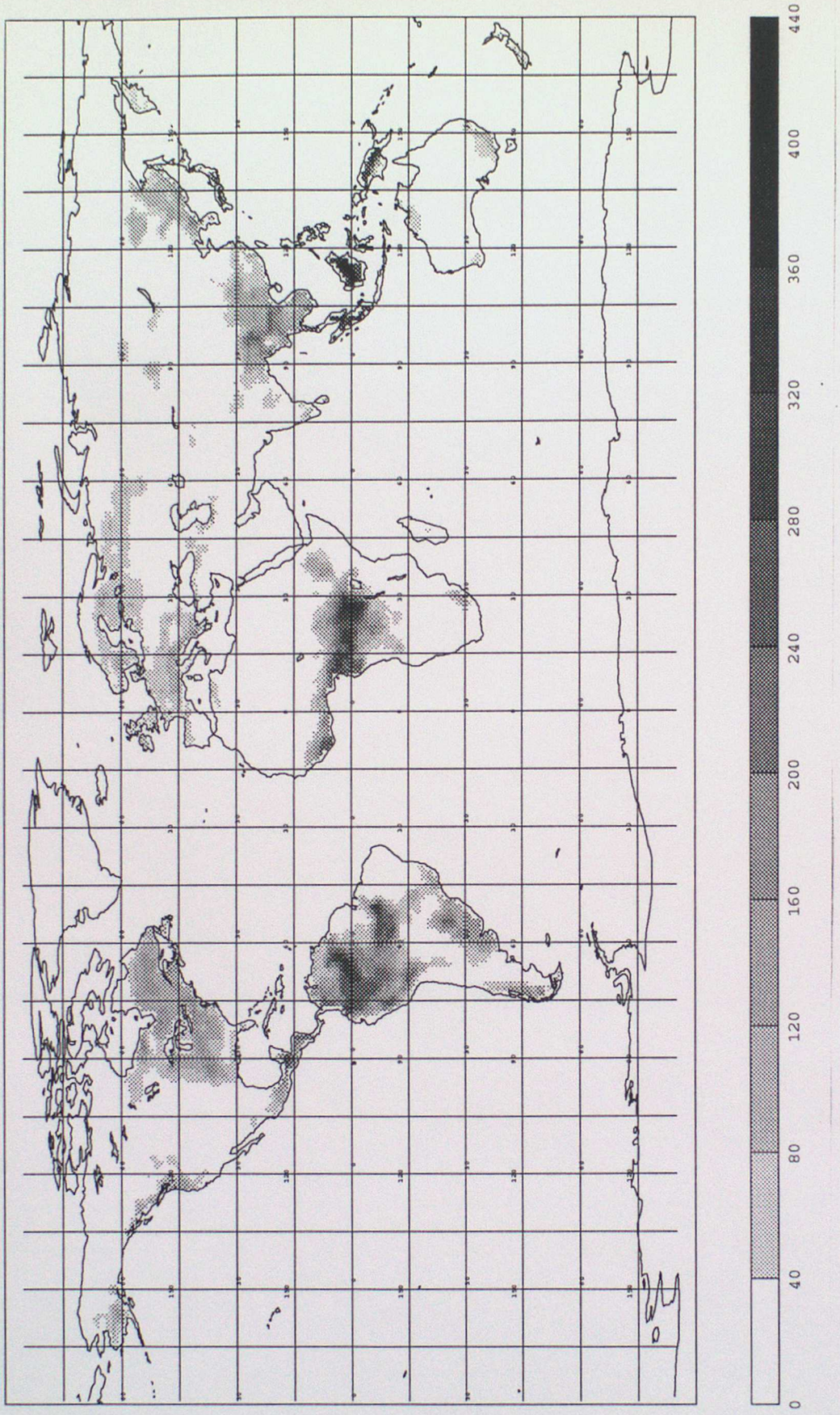

Figure 11: Soil moisture content at end of test experiment. Values shaded every 40kgm^{-2}.

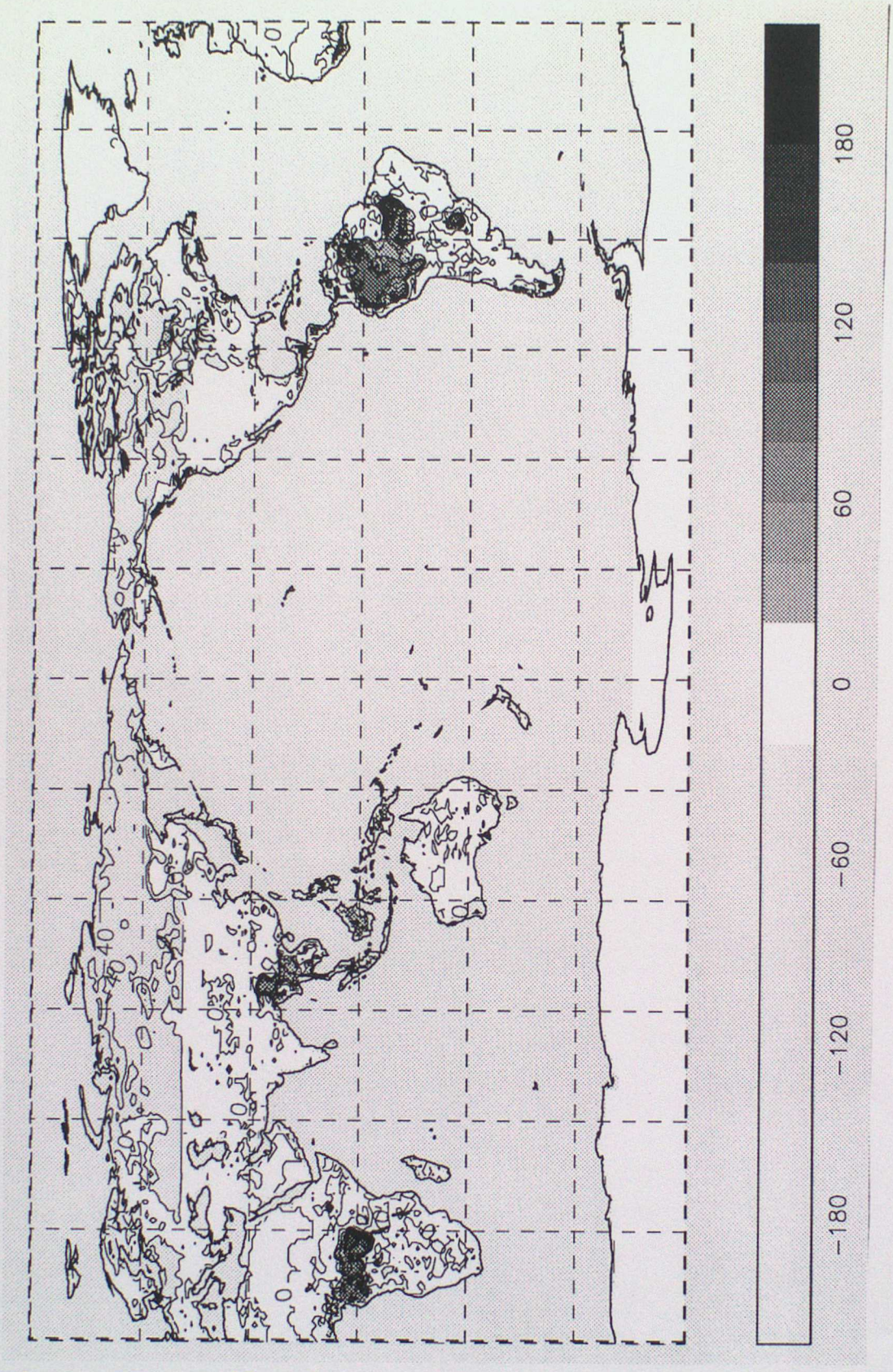

Figure 12: Soil moisture at end of test experiment minus soil moisture at end of control experiment. Contours drawn every 20kgm^{-2}.

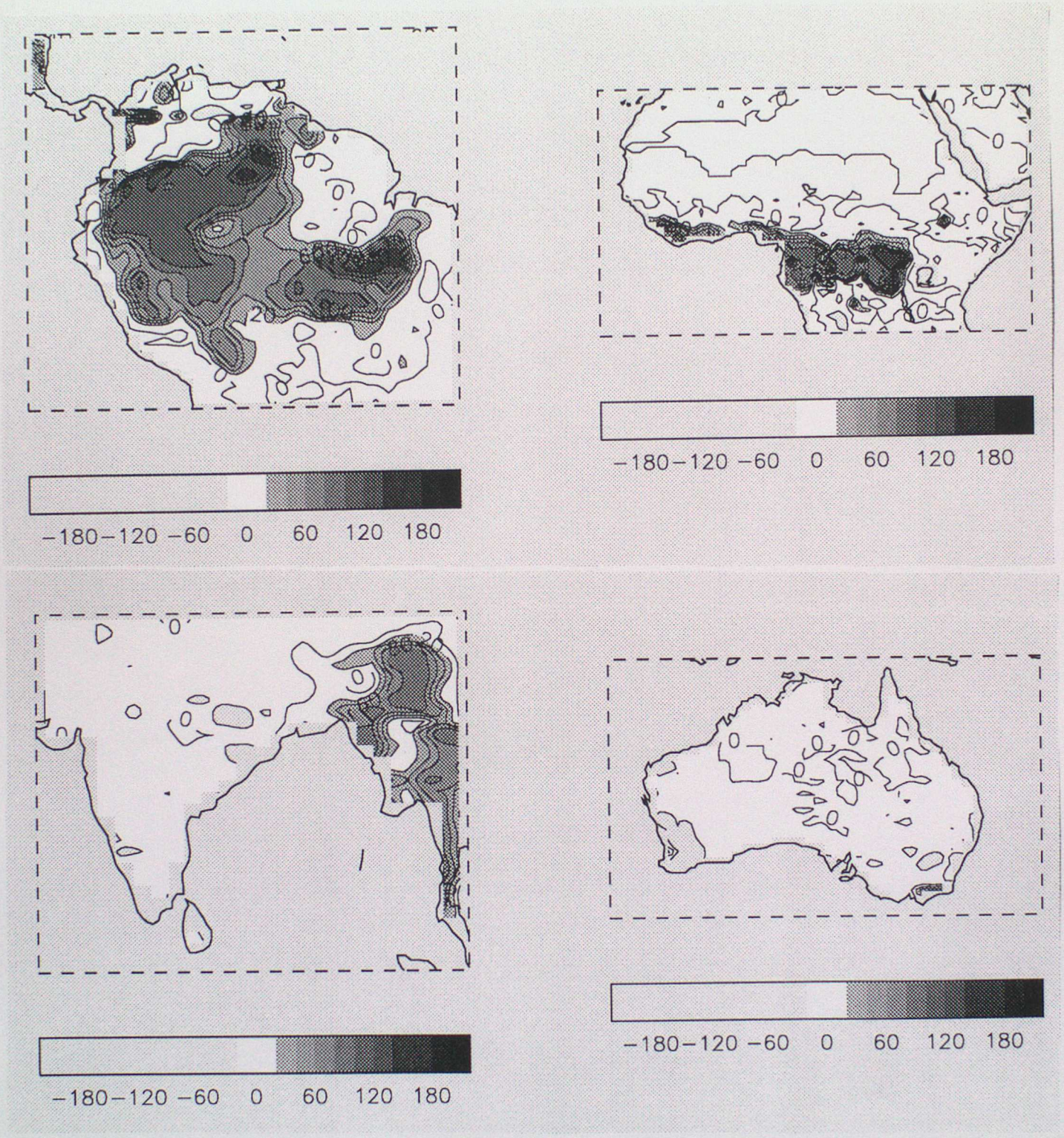

Figure 13: Soil moisture at end of test experiment minus soil moisture at end of control experiment. Contours drawn every 20kgm^{-2}.

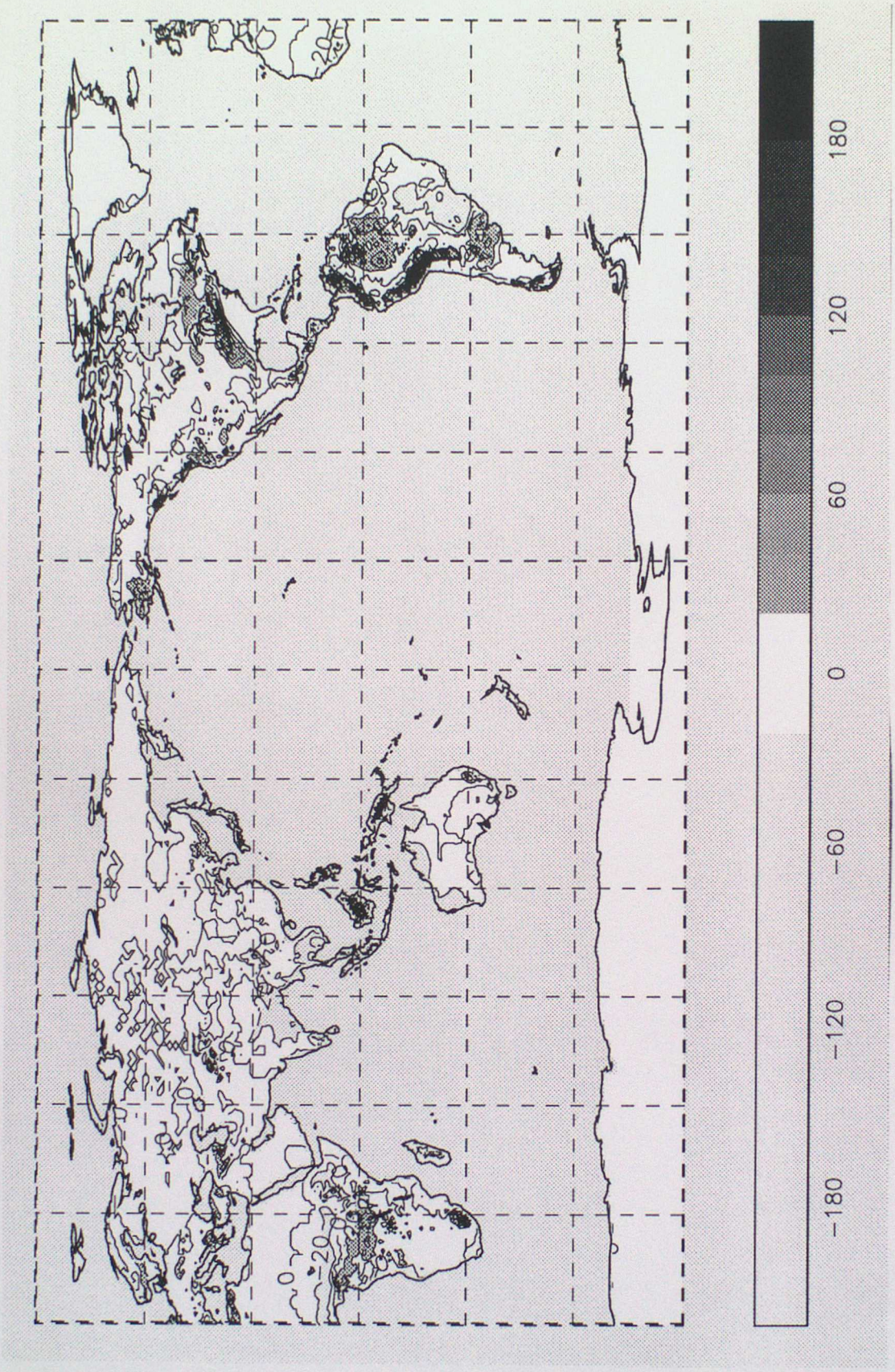

Figure 14: Change in soil moisture content in control experiment, (end minus start). Contours drawn every 20kgm^{-2}.

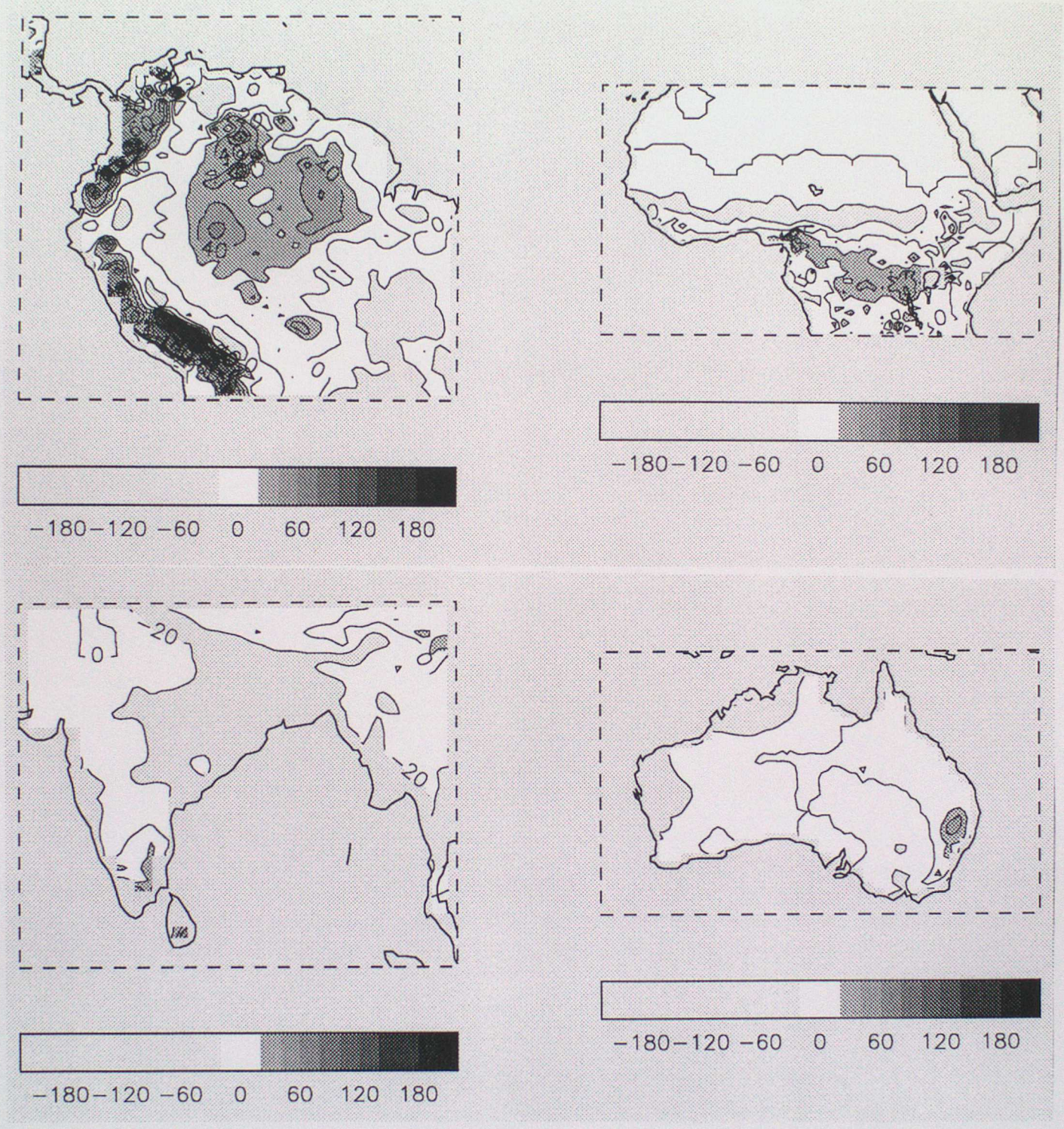

Figure 15: Change in soil moisture content in control experiment, (end minus start). Contours drawn every 20kgm^{-2}.

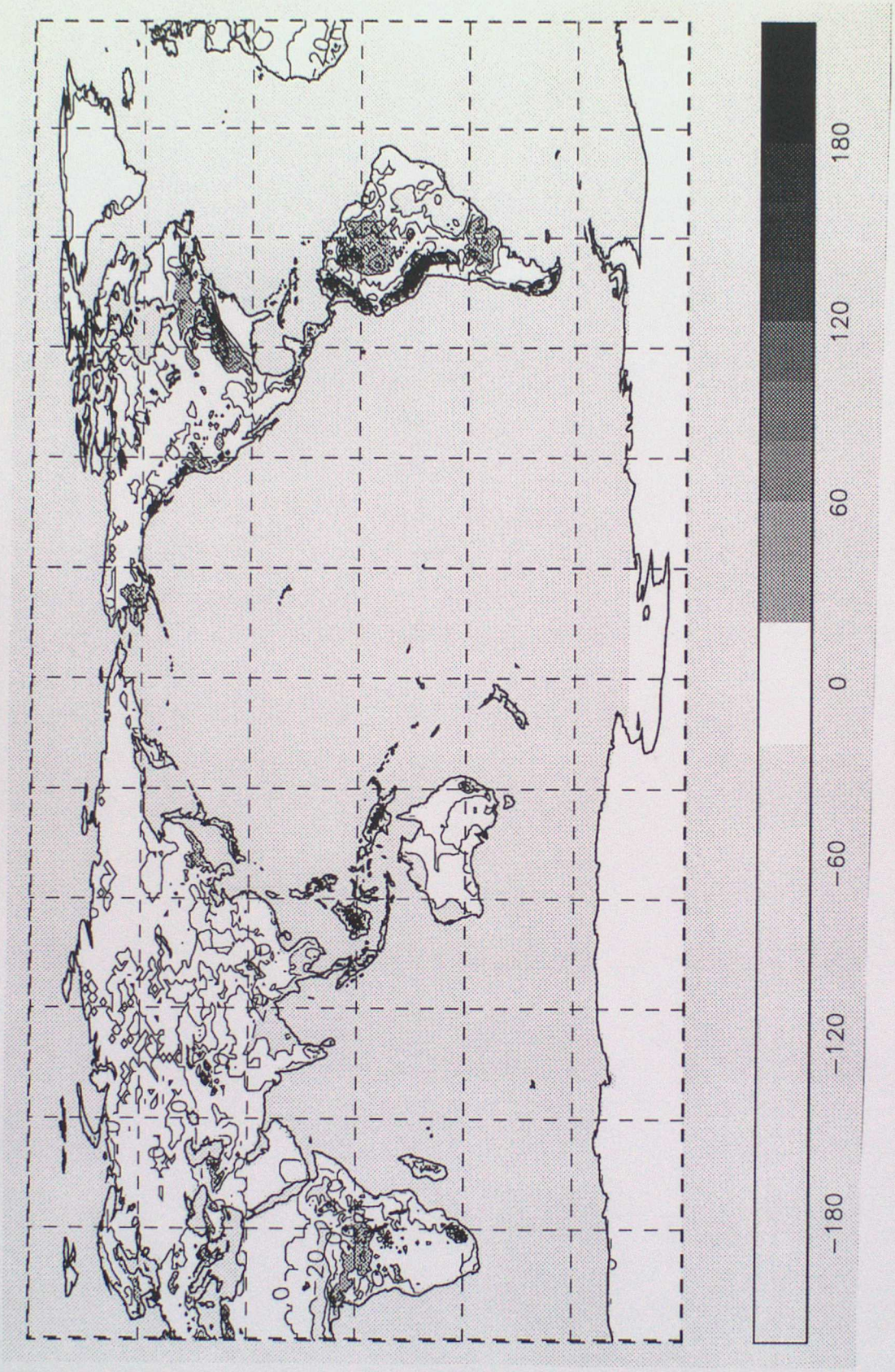

Figure 16: Change in soil moisture content in test experiment, (end minus start). Contours drawn every 20kgm^{-2}.

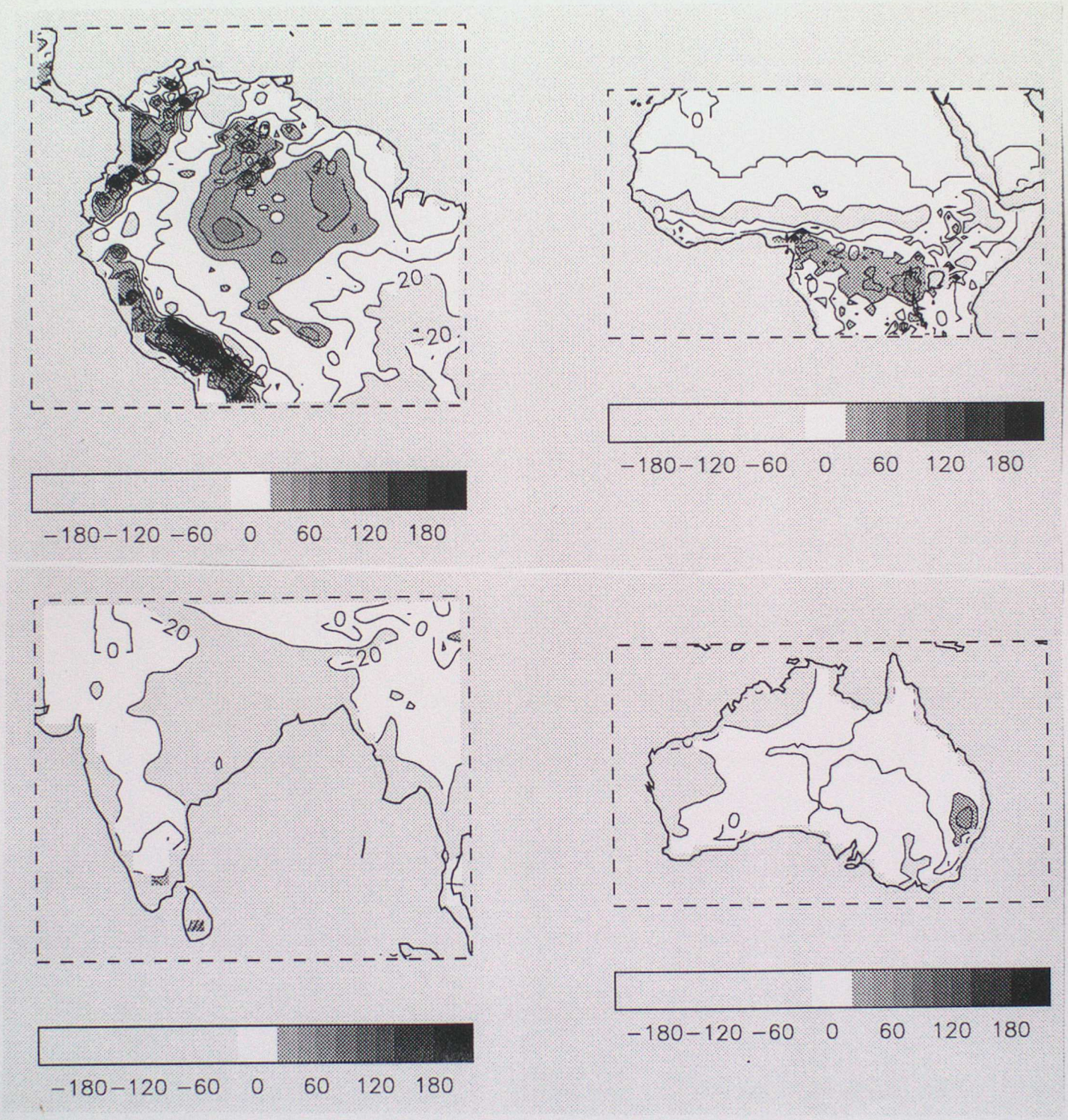

Figure 17: Change in soil moisture content in test experiment, (end minus start). Contours drawn every 20kgm^{-2}.

Figure 18: Zonal mean of soil moisture through control experiment at every 12 hours. (T+12 to T+72).

Figure 18: Zonal mean of soil moisture through control experiment at every 12 hours. (T+84 to T+144)

Figure 19: Zonal mean of soil moisture through test experiment at every 12 hours. (T+12 to T+72).

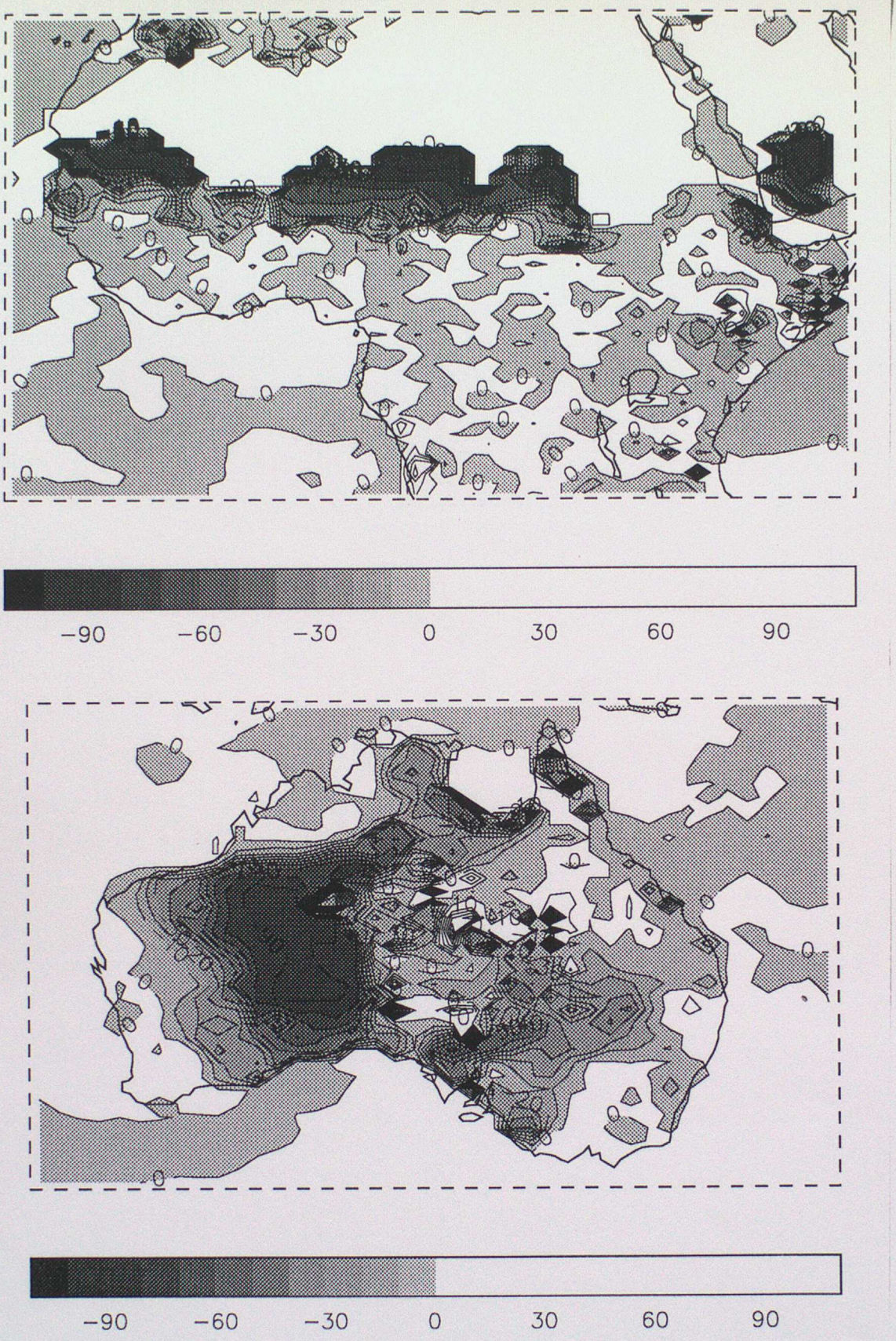

Figure 20: Percentage change in total surface and boundary layer flux in test experiment minus total surface and boundary layer flux in control experiment.

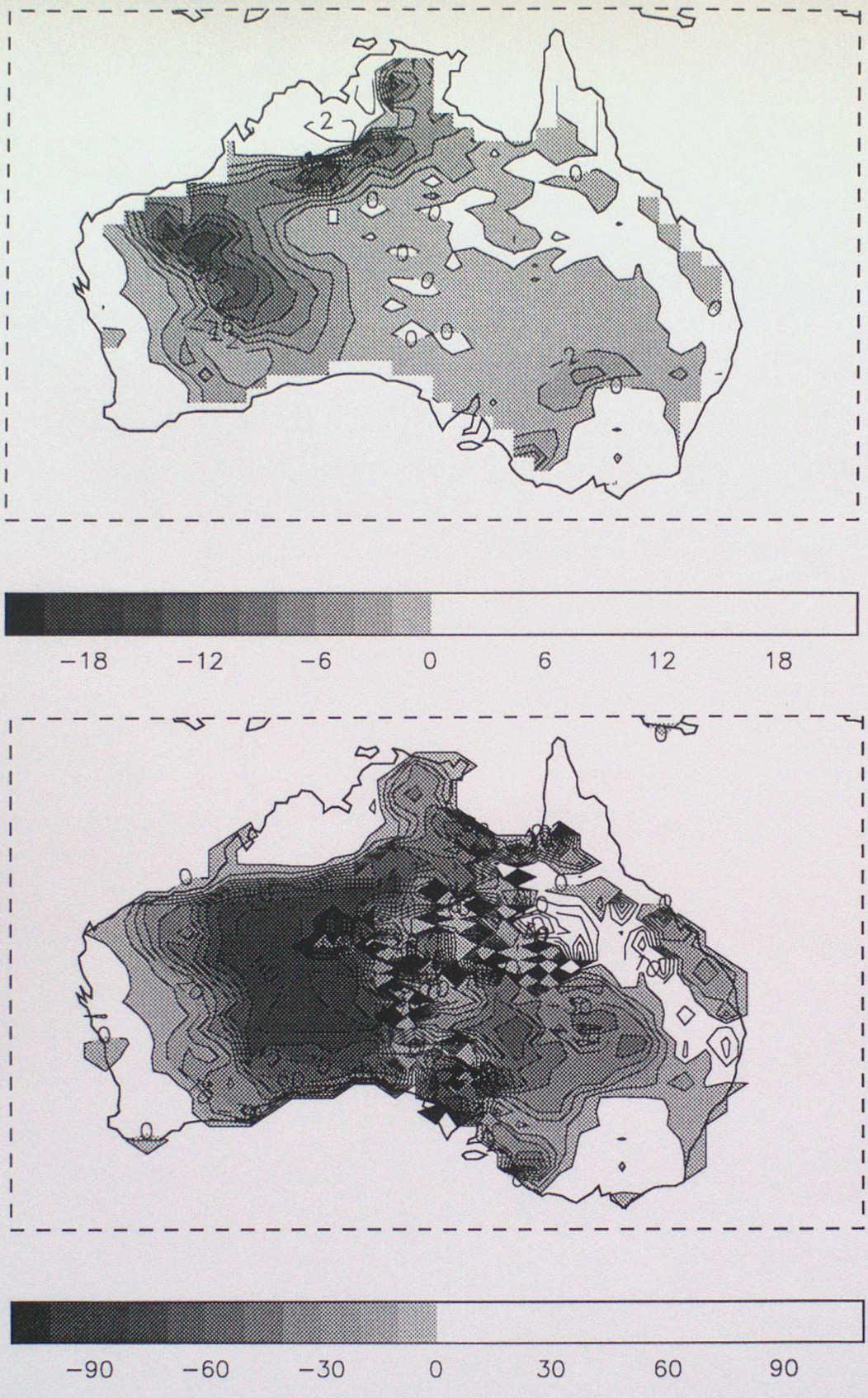

Figure 21: Total evaporation from soil surface in test experiment minus total change in evaporation from soil surface in control experiment. Top chart shows change, contours every 2kgm^{-2}s^{-1} and bottom chart shows percentage change.

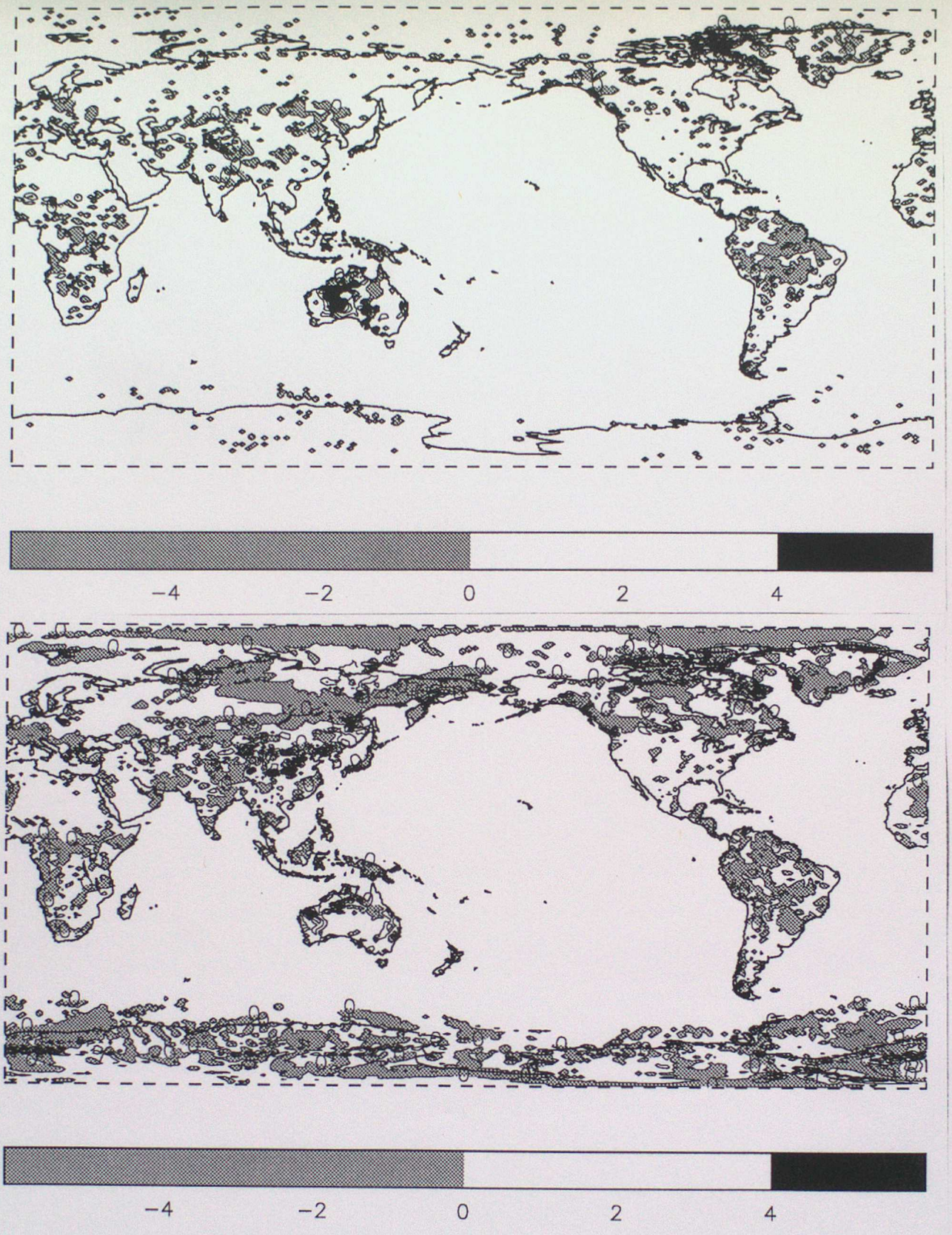

Figure 22: Surface temperature in test experiment minus surface temperature in control experiment. Contours drawn every 2K. Light shading used for values less than zero. Dark shading used for values greater than 4K. Top chart is T+24 and bottom chart is T+144.

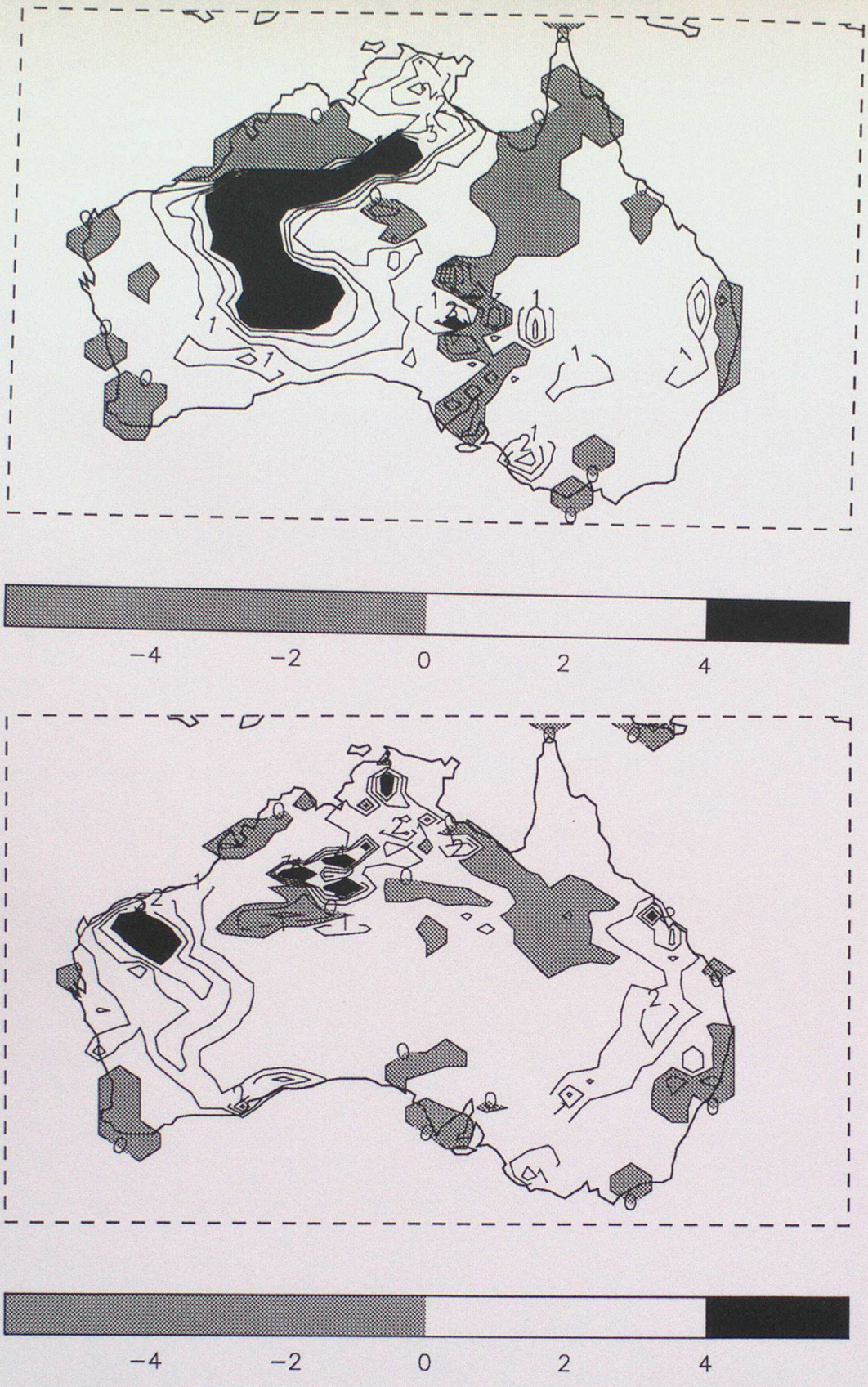

Figure 23: Surface temperature in test experiment minus surface temperature in control experiment. Contours drawn every 2K. Light shading used for values less than zero. Dark shading used for values greater than 4K. Top chart is T+24 and bottom chart is T+144.

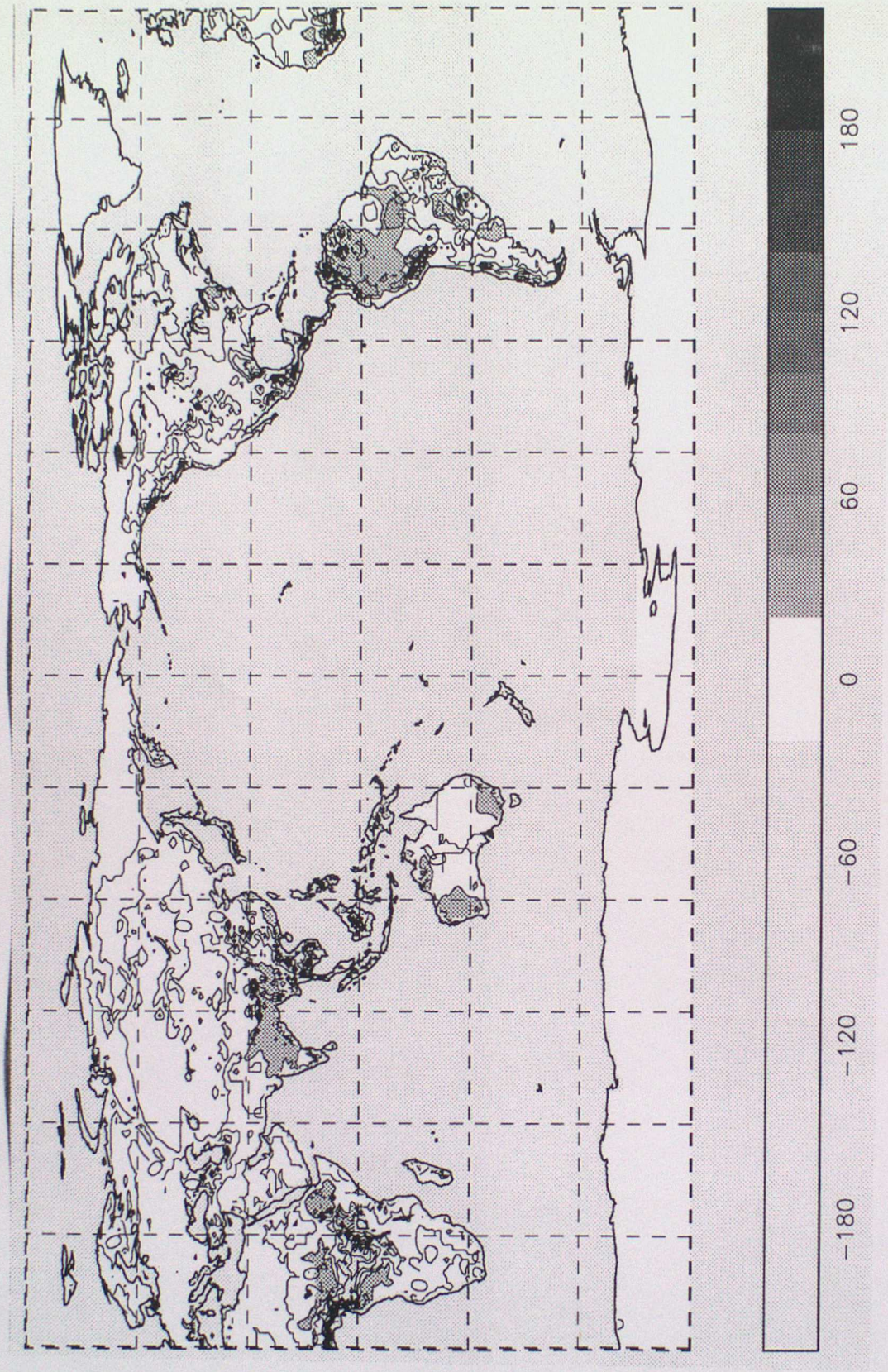

Figure 24: Soil moisture difference in operational model, reset to climatology in each day, and the paralle suite trial which has been allowed to run free. Contours drawn every 20kgm^{-2}.